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UNITED STATES

NAVAL AIR MISSILE TEST CENTER

TECHNICAL MEMORANDUM NO. 70

GSR NO. 30

PLANNING AND CONDUCTING RELIABILITY TEST PROGRAMS FOR GUIDED MISSILES

COPY NO. 246

20 JUNE 1952

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PLANNING AND CONDUCTING RELIABILITY TEST PROGRAMS FOR GUIDED MISSILES

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20 JUNE 1952

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Foreword

The U. S. Naval Air Missile Test Center was established at Point Mugu, California, by the Secretary of the Navy (SecNav ltr Op-24/mad Serial 1873P24 dtd 17 September 1946) effective 1 October 1946. It is an activity of the ELEVENTH Naval District. The Bureau of Aeronautics exercises management and technical control over this activity.

The primary mission of the Naval Air Missile Test Center is the testing and evaluation of guided missiles and their components. NAMTC is assigned cognizance over all facilities at Point Mugu, California, and outlying facilities on San Nicolas Island and the Santa Barbara Channel Islands, collectively referred to as the Sea Test Range.

★ ★ ★

Commander, Naval Air Missile Test Center ... Captain E. M. Condra, Jr., USN
Commanding Officer, Naval Air Station .... Captain M. T. Evans, USN
Director of Tests, Naval Air Missile Test Center..Captain A. C. Packard, USN
Chief Scientist, Naval Air Missile Test Center .... Dr. R. Weller

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planning and conducting reliability test programs for guided missiles

summary

Guided missiles must be made reliable essentially by ground testing methods, in particular by conducting comprehensive test-to-failure programs for all doubtful component types relative to all environmental conditions involved.

The desirability of conducting reliability test programs is, in principle, generally accepted. However, many people question whether such test programs can be performed economically and within the time limits set for the development of a guided missile.

In this study it is shown (1) that achieving and maintaining a satisfactory over-all reliability program is largely a problem of planning and organization, (2) that the reliability test program should be started when the missile is in its preliminary design stages and should be conducted, at high priority, throughout the missile development and continued as long as the missile remains in production, and (3) that, to accelerate the growth of the over-all reliability, appropriate test priorities should be established within the test program.

A variety of organizational concepts and tools are suggested that may help to solve the guided missile reliability problem economically and within a reasonable time.

introduction

One of the most difficult problems in developing guided missiles is how to achieve and maintain a satisfactory over-all reliability. The reasons for this are discussed in NAMTC Technical Report No. 75 and illustrated by two empirical diagrams, here reprinted as figures 1 and 2.

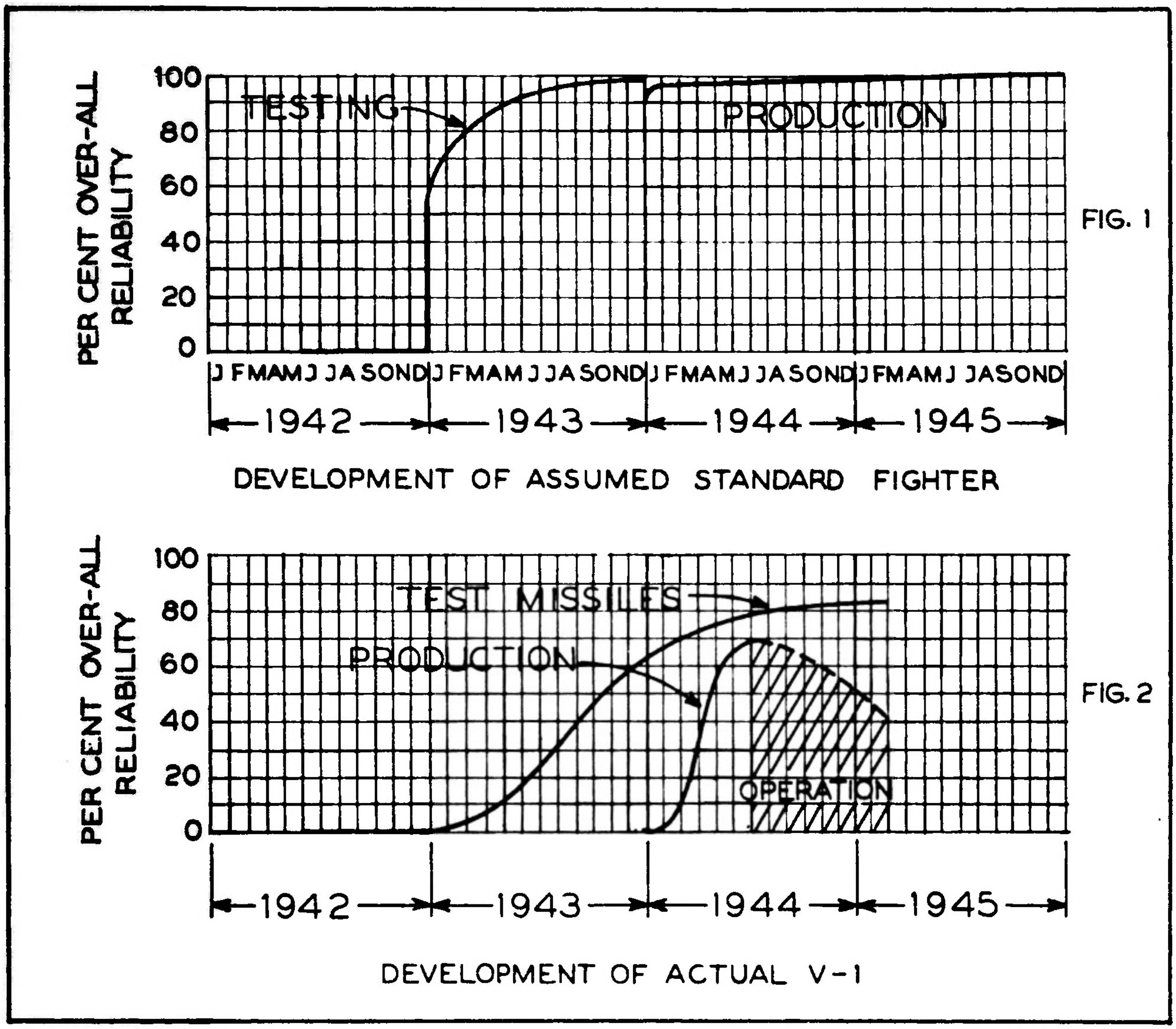

Figure 1 shows the characteristically rapid growth of reliability of a piloted aircraft. Figure 2 shows the growth of the over-all reliability typical of guided missiles and illustrates that (1) the initial reliability is practically zero, (2) the growth of the reliability is slow, (3) the maximum reliability that can be achieved is much lower than that of piloted aircraft, (4) the difficulty of maintaining even this low maximum is considerable once the missile is distributed for service.

This slow and arduous growth of over-all reliability is typical of <u>very complex</u>, <u>nonrecoverable</u>, <u>automatic</u> devices, such as guided missiles and, to a limited extent, torpedoes. Guided missiles, which are even more complex than torpedoes and also much less recoverable, impose the most

difficult reliability problem of all weapons. Consequently, satisfactory solution of the guided missile reliability problem requires extraordinary concepts and means, such as comprehensive test-to-failure programs that subject all component types to all stresses and environmental conditions.

Up to now, the need of planning for rapid development of over-all reliability has not been considered sufficiently because of the widespread and erroneous belief that guided missiles could be made reliable through application of the customary concepts applied in all "normal" technical fields, such as the development of piloted aircraft. For this reason experience in planning for the achievement of missile reliability is at present seriously lacking. It may take many more years of missile development and experience to establish a comprehensive basis for such planning by using ordinary industrial concepts. In any case, the time required would be much too long to prove beneficial for those guided missile types now being planned and developed.

An attempt is made in this study to delineate the basic factors and trends of reliability that must be considered in planning and performing a reliability test program, and to point out a variety of new concepts and tools for organizing such programs.

This report is the third in a series of NAMTC reports on reliability of guided missiles.* It is recommended that the reader study the first two reports for a better understanding of this third one.

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*NAMTC Technical Report No. 75: "A Study of Methods for Achieving Reliability of Guided Missiles."
NAMTC Technical Report No. 84: "General Specifications for the Safety Margins Required for Guided Missile Components".

INDEX OF SYMBOLS

n	Number of components in missile
$p_1' : p_2' : p_3' \cdots p_i'$	Indices of component reliability
$q_1' : q_2' : q_3' \cdots q_i'$	Indices of probability of failure of components
$P'_{over\text{-}all}$	Over-all reliability of missile
Q_{true}	True contribution of a "test case" to the knowledge of the probability of failure of missile
m	Number of times a component type occurs within a missile
$H = m \cdot q'$	"Hazard of Failure" caused by a component type as a result of one environmental condition
$H_{total} = \Sigma\, m \cdot q'$	"Hazard of Failure" caused by a component type as a result of all environmental conditions
$\Sigma\, H_{total}$	"Grand Hazard of Failure" exerted by a component type upon all missile types involved
a	Cost of procuring one test unit
b	Cost of conducting one test
c	Cost of preparing a particular test case
N	Number of units required for a test case
$PI = \dfrac{m \cdot q'}{N(a + b) + c}$	Priority Index
$\Sigma\, PI$	Grand Priority Index indicating the urgency of the various test programs within the total guided missile development program

A

PART I

basic concepts for the planning of a reliability test program

DESIGNING OF THEORETICAL PLANNING CURVES

A family of theoretical curves, showing an assumed growth of over-all reliability for guided missiles, is presented in figure 3.

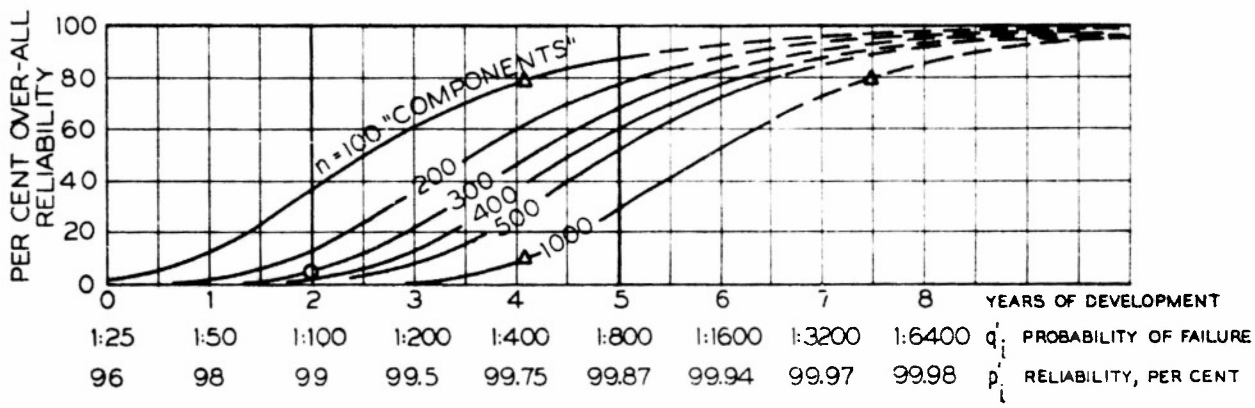

Fig. 3. Growth of the Over-All Reliability as a Function of the Rate of Component Development.

The curves are obtained on the basis of the formula for the over-all reliability

$$P'_{over\text{-}all} = p'_1 \cdot p'_2 \cdot p'_3 \cdots p'_i \cdots p'_n \;*$$

The terms p'_1, p'_2, p'_n, denote the Indices of Reliability** of the individual components of a missile; n indicates the number of all doubtful components to be scrutinized and is used here as a measure of the "Reliability Complexity"* of a missile. The letter p'_i indicates the general level of component reliability achieved at the various stages of development. For simplicity of discussion it may be assumed that all doubtful missile components have the same reliability, expressed by p'_i. Thus one will arrive at the short form:

$$P'_{over\text{-}all} = p_i'^{\,n}$$

This is the form used in the computation of the curves in figure 3.

* See NAMTC Technical Report No. 75, pages 13 and 14 and Figure 3.
**For discussion of "Indices of Reliability" see NAMTC Technical Report No. 84, pages 46-50.

In designing the curves of figure 3, two more parameters must be assumed:

1. The level of component reliability available at the beginning of a development. This level is assumed to be p_i'(initial) = 96 per cent. Such a low level may be appropriate for much of guided missile development at its present stage.

2. The rate of growth of the reliability of all components. The assumption is made that the chance of failure of components can be halved every year, for example, q = 4; 2; 1; .5 .... per cent. In this case the ratio of the number functioning units to one failing unit will progress as follows: 25:1; 50:1; 100:1; 200:1;··· (see abscissa in figure 3). The assumption of such a rate of growth may be justified if one realizes that the knowledge of the techniques and "arts" related to guided missiles at present is still meager.

One may view these parameters more optimistically or more pessimistically. Whatever one's attitude is, the family of curves need not be recomputed and redrawn. One has only to shift the origin of the time scale to the desired p_i' (initial), and expand or contract the time scale to accord with the desired rate of growth.

In spite of the theoretical character of these curves, they can be used for reaching important conclusions in the planning and conducting of reliability test programs. This will be discussed in the next chapter.

ANALYSIS OF THE PLANNING CURVES

Reliability at the Beginning of a Missile Development

Figure 3 shows that, at the beginning of a missile development, the theoretical over-all reliability is practically zero, if p_i' (initial) = 96 per cent. This would be true for even a relatively simple missile (n = 100, for example). In order to start with a markedly better initial over-all reliability for complexity of n = 100, the initial level of component reliability should at least be as high as p_i' (initial) = 99 per cent. This, however, cannot be expected because many of the components are not yet designed, and certainly not tested, at the outset of missile development.

> *First Conclusion: It is very desirable that the development of a guided missile be based as far as possible on components and elements that are already developed to a high reliability, and which are standardized for use in guided missiles.*

Reliability Required for the Flight Test Phase

Flight test programs for guided missiles can be subdivided according to the three main categories of tasks:

1. Determination of the maximum stresses and environmental conditions during launching and flight.

2. Determination of the optimum adjustments of performance parameters, such as the feed back ratio of servo loops.

3. Determination of the hit probability of the weapon.

The progress and success of each category of flight tests obviously depends largeiy on the reliability of the missiles used for the various tests.

Figure 3 demonstrates that when the flight test program can be begun after, for example,* 2 years of development, the over-all reliability of a flight test missile is probably no better than a few per cent. (As an example, see ordinate for n = 300 at 2 years.) Consequently, the expensive and time-consuming flight test progarm obviously will suffer greatly from numerous missile failures that will, frequently, have nothing to do with the actual objectives of the various test flights.

Second Conclusion: The majority of "series components" ought to be developed to a satisfactory degree of functional reliability before the flight test program, employing more or less complete test missiles, is in full operation. Consequently, a reliability test program must be started at the very beginning of a missile development and must be accelerated with every resource.

Occasionally the objection is made that with the institution of a reliability test program the total expense of a missile development would become insupportable. Let us see what the economic advantages of such a program are.

*The "beginning" of the actual flight test program cannot be defined precisely because it should be preceded by the firing of dummy missiles and more simple test missiles required to determine the environmental conditions during launching and flight. The beginning of the flight test program as understood in this study may be defined as "the stage of development where the efforts and expenses for flight test missiles and for flight testing become a dominant factor in the over-all economy of the development."

Fig. 4. Growth of Over-All Reliability Accelerated by Doubling Rate of Component Development.

In figure 4 the theoretical curve of growth of a missile comprising n = 300 doubtful components is reprinted from figure 3 as an example. At the outset of the actual flight test program (which it may be assumed will start 2 years after the project has begun), the over-all reliability would be as low as 5 per cent ($0.99^{300} = 0.049$). (See figure 4.) Accordingly 20 missiles would have to be expended in order to achieve one completely successful firing. If all the components could be improved at twice the rate originally assumed, the dashed curve in figure 4 would be obtained, which will indicate an over-all reliability of 47 per cent ($0.9975^{300} = 0.472$) at the start of the flight test program. Now only two missiles would have to be fired in order to achieve one complete success! It is thus apparent that the over-all reliability in this case would be raised not by the factor 2., as one might offhandedly presume, but by the factor 10.

This simplified example shows how an accelerated reliability test program could result in a saving of 18 (i.e., 20-2) expensive test missiles per missile successfully fired. In this stage of development missiles are particularly expensive and valuable to the development program even if they are not elaborately equipped. Thus, assuming an average cost for one missile of $100,000, the total savings would amount to $1,800,000 for each missile successfully fired.

One may consider this figure as somewhat exaggerated because a flight test missile that failed at some later stage of its flight may yield at least some partial test results. However, in the third stage of flight testing, where the pattern of hits is to be determined, a missile must at least be capable of reaching the target area before it can be considered as contributary to the pattern of hits.

At any rate, it is believed that even with a fraction of such savings one can easily double the usual low rate of component improvement.

These considerations do not give the complete economic advantages of a reliability program. One must realize that many more, possibly hundreds of missiles, could be "saved" (i.e., would be successes instead of duds) during training, and in service use. Such savings may, in some cases, exceed the expenses of a complete reliability test program by several orders of magnitude!

Third Conclusion: The conduct of a thorough reliability test program can be considered as a highly economical method for achieving reliable service missiles.

The Component Reliability Required at the Beginning of Mass Production

The most critical stage in the development of a guided missile will occur when mass production is to be started. By that time, and not later, proof must have been established, through extensive flight testing and under simulated combat conditions, that the missile type has actually attained an over-all reliability that is satisfactory from the military standpoint.

There need be only one weak component type to make a missile undeservedly unserviceable. If such faulty component types are still present at the beginning of mass production, one can hardly prevent them from being caught up in the inexorable and inflexible process of mass production, and so become hidden hazards to the success of the weapon.

Fourth Conclusion: Components that are found to be unreliable shortly before the beginning of mass production must be perfected and made reliable with utmost dispatch. Very high priorities must be granted for the testing and improving of such "late" components.

The Scrutiny of Component Reliability During Mass Production

One could presume that a reliability test program could be closed or relaxed once mass production and quality control are in full operation. Such a view, however, entirely misinterprets and underestimates the purposes of reliability scrutiny and reliability testing.*

Mass production of a new missile involves a cumbersome gearing up on a broad industrial basis, with new firms and personnel that are oftentimes inexperienced. As a result, a considerable lowering of the general level of component reliability, as well as the occurence of "erratic" components must be expected. The over-all reliability, being extremely sensitive to such setbacks, may easily drop to an entirely unsatisfactory level. One must realize that the natural tendency of the over-all reliability of a

*For the purposes of reliability testing see page 40.

guided missile is to drop (see figure 2). If, therefore, the specific testing and scrutinizing of the over-all reliability were discontinued during mass production, the missile weapon would soon become unserviceable without anyone realizing it.

In addition, one must expect that during the period of production, distribution, and operation, some of the environmental conditions (as in transportation, storage, handling, etc.) will become much better known, and will call for alterations in numerous types of components and necessitate still further reliability testing and scrutinizing.

Fifth Conclusion: Reliability test programs must be continued as long as a missile type is being produced. The more a guided missile type has proven its military value, the more such a test program needs to be intensified.

The Importance of Time Saving to the Military Value of a Weapon

The time required to develop a new weapon to an acceptable level of military value is of primary importance for the chances of success in any development. A new weapon that may be extremely valuable 2 years from today may be already obsolete in 4 years. Thus the time factor may outweigh all other considerations.

Occasionally one hears the objection that, because of the overwhelming importance of the time factor, a cumbersome and time-consuming reliability test program should be omitted or greatly cut down in favor of speeding up flight testing. This is a dangerous mistake! In order to raise the reliability of guided missile components to the required extremely high level, one can rely very little on flight testing and not at all on service use, in contrast to the case of piloted aircraft.

Sixth Conclusion: Speeding up a reliability test program not only will reduce the total expense of a development, but will, through a reduction in the time of the missile development, directly increase the military value of the guided missile.

Simplicity in Design

Figure 3 demonstrates the influence of the complexity, n, on the time required for a project development. For example, a missile type comprising n = 100 doubtful components might attain an 80 per cent over-all reliability after 4 years of development. A missile comprising n = 500 components on the same quality level would need about 7.5 years (or more, as will be shown later) to reach the same reliability.

Seventh Conclusion: In the interest of saving time, both from the economical as well as the military standpoint, it is necessary to strive for simplicity in design.

Achievability of Very High Levels of Component Reliability

With an increase in the complexity, n, the curves shift more and more to the right hand side of figure 3. They are, however, identical with respect to their S-shape and slant. This could lead one to believe that very complex missiles (n = 1,000, for example) would, in principle, have the same chance of becoming as reliable as simple missiles (n = 100, for example), after an initial period of "below 1 per cent reliability" has been overcome. (For the example of n = 1,000, this period would extend over about 3.5 years, according to figure 3.)

Such a belief, however, is certainly much to optimistic! Experience has shown that it is increasingly difficult to achieve perceptible gains at the higher levels of component reliability. Some reasons for this are: (1) With a rising level of component reliability, general expenditures for the tests need to be increased progressively. (2) If a "lot" is inspected again and again by various inspectors, more and more of the defective units will be detected. Therefore, the higher the reliability bracket the less confidence statistical test results merit. (3) The detection of "assignable" causes of failures becomes increasingly more difficult the closer the core of the constant system of chance causes is approached.* (4) We are approaching the limits of human fallibility.

Eighth Conclusion: It is much more difficult, expensive, and time-consuming to double the level of component reliability in the region of 99.9 per cent, ($q' = 1:1{,}000$) than in the region of 99 per cent ($q' = 1:100$) or in the region of 90 per cent ($q' = 1:10$).

*Ninth Conclusion: Complex missiles are particularly handicapped by the fact just mentioned. There are not only larger numbers of components (n) to be developed and scruntinized, but these components require, at the same time, a much higher level of component reliability (p_i') for achieving a specified over-all reliability. It should be remembered that the difficulty of making a complex system reliable is roughly proportional to the square** of the number n of the components.*

The facts presented in the eighth and ninth conclusions prove that the family of curves in figure 3 gives an obviously too optimistic picture and should therefore be modified. This can be done by progressively expanding the time interval required for doubling the level of component quality. In figure 5 it is tentatively assumed that each subsequent time interval required for doubling the level of reliability would be 10 per cent larger than the preceeding interval (see q_i' and p_i' scales). Thus, by simply

*For definition of "assignable" causes and "chance" causes, see W. A. Shewart, "Economic Control of Quality of Manufactured Products," pages 12 and 130.

**See NAMTC Technical Report No. 75, page 16, point 3.

replotting the curves of figure 3, a more realistic picture of the general trends of reliability development is obtained. Compared with figure 3, the curves of growth in figure 5 are progressively stretched.

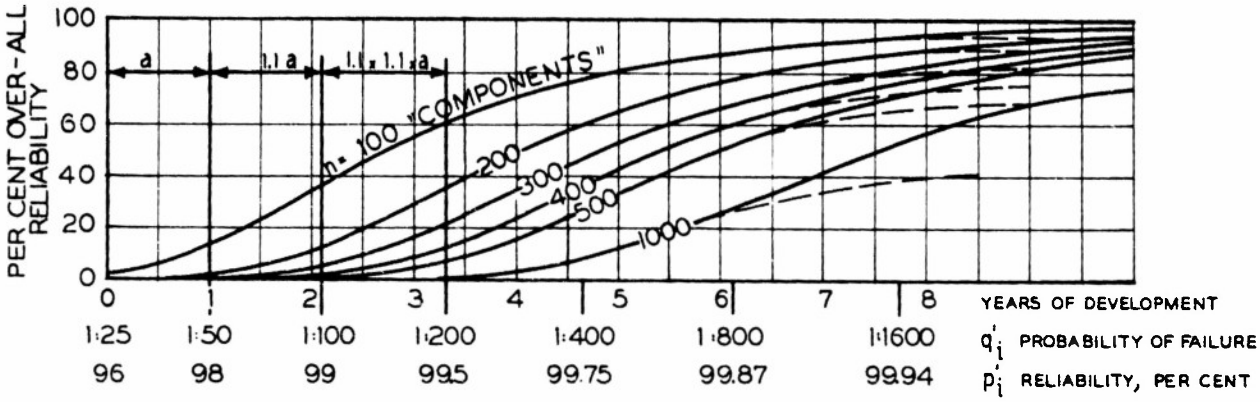

Fig. 5. Growth of Over-All Reliability, Modified.

Figure 5 will be discussed by means of two examples: (1) A simple missile, containing n = 100 critical or doubtful components, might attain an over-all reliability of 70 per cent after 4 years of development ($p_i' =$ 99.63; $q_i' = 1:300$), and (2) a complex missile, containing n = 1,000 components of the same quality level ($p_i' = 99.63$ per cent) would only attain a 3 per cent over-all reliability in the same period of development. To achieve the desired 70 per cent over-all reliability, the level of component reliability would have to be raised as high as $p_i' = 99.975$ per cent (or $q_i' =$ 1:3,500, i.e. on the average only 1 unit in 3,500 may fail). This might be achieved after 9 years of intensive development—or never, as will now be discussed.

It is very questionable whether such high levels of component reliability are at all feasible. With increasing complexity and cost, the total number of missiles that can be produced would unavoidably decrease. The benefits to quality derived from modern methods of mass production and quality control will decrease also. The number of component units will finally become too small for <u>testing to failure</u> on a sound statistical basis.

On the other hand, <u>flight testing</u> will become a more and more unacceptable risk, firstly, because of the very high cost of one test missile, and, secondly, because of the very slight chance that such a complex missile will function properly during its single* flight.

Tenth Conclusion: The <u>maximum</u> over-all reliability achievable will decrease sharply with <u>increasing</u> complexity.

*Recoverable test missiles are less critical in this respect. Such missiles are, however, feasible only in few cases.

To illustrate these adverse influences, the upper sections of the curves in figure 5 are leveled off tentatively (see dashed branches). The curves for the more complex missiles are leveled off at an earlier stage, because it will be much more difficult to scrutinize continuously the many components of a very complex missile, than to evaluate only the few components of a simple missile.

The Chances of the Isolated, Very Complex Missile

A very complex missile being built in one, or a few, prototype units only, presents the extreme case. Even if it could be proved theoretically that such a missile would function, there is no chance of practical application because it is impossible to achieve a reasonable over-all reliability.

> *Eleventh Conclusion: Very complex guided missile types being built in one, or few, units only must be considered completely impracticable.*

The following parts of this study are devoted in particular to the question of: How can the growth of the over-all reliability be accelerated?

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PART II

the priorities within a reliability test program

GENERAL

In NAMTC Technical Report No. 75 it was recommended that within the organization of the missile development contractor, and within the sponsoring government agency, there be designated for each missile project a "reliability co-ordinator." The task of this co-ordinator would be to stimulate testing activity for obtaining reliability data and to gather and evaluate these data systematically.

In the planning of a reliability test program the reliability co-ordinator will be confronted with a long chain of combinations of components and environmental conditions, called "test cases," the reliabilities of which are unknown and possibly critical. One should always keep in mind that a great many sensitive components will suffer not only from one kind of stress or condition but from several. Thus the chain of weak links becomes correspondingly longer - and weaker.

As pointed out in Part I, these many doubtful combinations should be tested at once and at very high priority in order to achieve the urgently needed rapid growth of the over-all reliability.

Even if high priority is granted to a reliability test program as a whole, the test capacities, i.e., manpower, facilities, and material, will always be insufficient for starting and conducting all the many test cases in the same early period. As a result, many of the test cases, even if they are known to be, or suspected of being, critical to the missile, <u>must of necessity be postponed</u>. Again and again the question will arise as to which of the many test cases should be given priority within the reliability test program.

Test priorities result often merely from the competition for the limited test facilities and little or no consideration is given to the vital question of how the growth of the over-all reliability can best and most efficiently be accelerated.

This task belongs obviously in the realm of the reliability co-ordinator, who is trained to see the complete picture of guided missile reliability and who is largely responsible for it.

In determining the test priorities the reliability co-ordinator should be guided predominantly <u>by the demand for the most rapid growth of the over-all reliability</u>. For this purpose a priority system is suggested that

will help to separate out the test cases most likely to contribute to the growth of the over-all reliability.

The "Hazard of Failure," $H = m \cdot q'$.

For determining the test priorities, a rational nnd convenient formula must be derived. For this purpose one has to consider:

m = the frequency of occurence of a component type in a missile
q' = the actual, or estimated index of probability of failure of that component type relative to a certain kind of stress.

By multiplying these two factors, the "hazard of failure," $H = m \cdot q'$, is obtained, which indicates approximately how much a "test case" could contribute to the over-all probability of failure, $Q_{over\text{-}all}$, of a missile. For example, a rate gyro that occurs twice in a missile, and that has a probability of failure of 3 per cent, will cause a failure hazard of $m \cdot q' = 2 \cdot 3 = 6$ per cent. A type of vacuum tube that is used 48 times in a missile, and has a probability failure of "only" 0.5 per cent, would cause a failure hazard of $m \cdot q' = 48 \cdot 5 = 24$ per cent. It is evident that the vacuum tube should have a much higher priority in the reliability test program than the gyro.

Thus the hazard of failure, $H = m \cdot q'$, is a handy tool for determining in what order the many test cases that are competing for priority should receive attention.

RELATION BETWEEN "HAZARD OF FAILURE" AND "PROBABILITY OF FAILURE."

The truth of the statement that the hazard of failure, $H = m \cdot q'$, indicates directly the contribution Q to the over-all probability of failure of the missile, is not self-apparent. In fact, persons familiar with statistics may object that the statement is inaccurate Thus some explanation is required.

The true contribution Q_{true} of a component type to the over-all probability of failure of a missile is obtained by the formulas:

1. $P' = (1 - q_1')(1 - q_2')(1 - q_3') \cdots (1 - q_i') \cdots (1 - q_m')$
2. $Q_{true} = 1 - P'$,

where P = probability of success, or the reliability, of a group of m units, having probabilities of failure of q_1'; q_2'; $q_3' \cdots q_m'$.

These formulas are correct though not handy for the purpose of scrutiny. Much more practical is the arbitrary concept that the contribution Q equals simply the sum of the q''s of the m units occuring in the missile:

$$H = q_1' + q_2' + q_3' + \cdots q_i' \cdots q_m'$$

or, because all m units are of the same type:

$$H = m \cdot q_i'$$

This is the hazard of failure, H, as defined above. However, as is shown in figure 6, H is not always identical with Q_{true}:

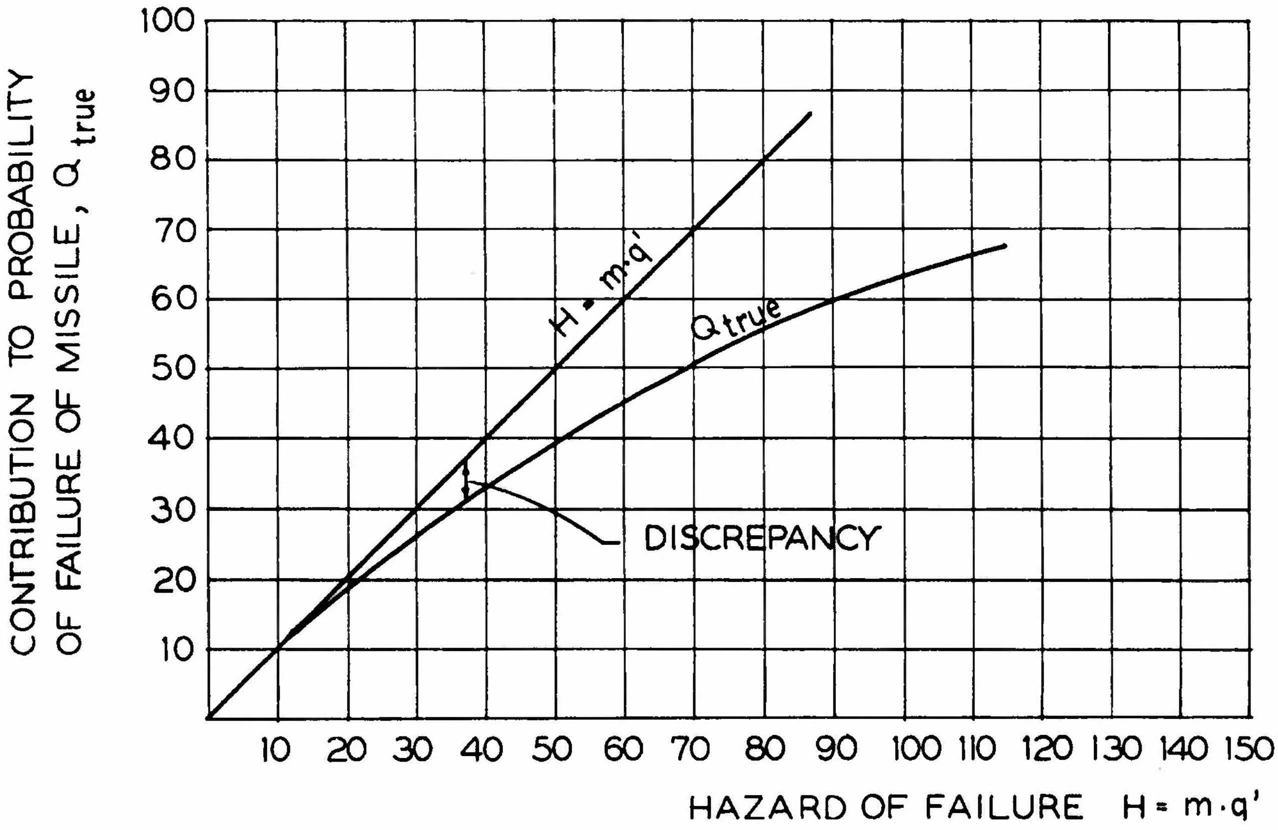

Fig. 6. Hazard of Failure, $H = m \cdot q'$, Versus the True Contribution, Q_{true}.

Figure 6 shows that the hazard of failure, $H = m \cdot q'$, is practically identical with the true contribution, Q_{true}, <u>only for small values of $m \cdot q'$.</u> The discrepancy between H and Q_{true} becomes increasingly larger as $m \cdot q'$ increases. This, however, does not diminish the usefulness of the simplified concept, because:

1. The great majority of all component types fall into the low range of $m \cdot q'$ (i.e. below 5 ÷ 10 per cent). If this were not the case, a guided missile would be hopelessly unreliable.

2. It is very desirable that the urgency of the test cases showing high hazards of failure $m \cdot q'$ be even overemphasized through the priority scale. (See example of vacuum tube on page 16.)

Thus, one arrives at the conclusion that the hazard of failure, $m \cdot q'$, though not always exactly identical with the true contribution Q_{true} can be considered an appropriate tool for determining the test priorities.

THE "PRIORITY INDEX," PI

If the hazard of failure, $H = m \cdot q'$, were to be used as the only criterion for determining test priorities, it might frequently occur that one bulky test case would block several others, which together could possibly contribute much more to the urgently needed growth of the over-all reliability of the entire missile. This should be avoided carefully. Consequently, one must consider not only the hazard of failure, $H = m \cdot q'$, in determining the test priorities, but also those factors that tend to retard the performance and the completion of the tests. Such factors are:

a = cost of procurement of one test unit, expressed in units of a thousand dollars,

b = cost for conducting and evaluating one single test, expressed in units of a thousand dollars.

c = cost for preparing a particular test case, i.e., cost of special testing facilities, and of establishing the theoretical basis for the tests, in units of a thousand dollars;

N = number of units, or sample size, required for determining the reliability.*

If one uses these factors and notations, and also the "Hazard of Failure", $H = m \cdot q'$ (defined above), a "Priority Index," PI, can be formulated as a tool for determining the priorities within a test program:

$$\text{Priority Index, PI} = \frac{m \cdot q'}{N(a + b) + c} = \frac{\text{Failure Hazard}}{\text{Cost of Testing}}$$

The greater PI, the better the chances that a component type, by being tested and improved, will contribute to the rapid growth of the over-all reliability of a missile. Consequently, it is proper to place test cases with large priority indices well ahead in the general reliability program.

TWO EXAMPLES OF APPLICATION

1. Component type A, occuring only once (m = 1) in the missile, may have a known, or estimated probability of failure of $q' = 5$ per cent. Let us assume that a sample of N = 15 units is to be tested. Cost of procure-

*The problem of choosing the "best" sample size will be discussed in detail in Part III of this study. For this phase of the discussion it may be accepted that in choosing the sample size an optimum can be approached.

ment of one unit may be \$100, ($a = 0.1$). The cost of conducting and evaluating of one test may be estimated as \$50 ($b = 0.05$) and the expense of preparing the test as \$250 ($c = 0.25$). Then

$$PI = \frac{1 \cdot 5}{15(0.1 + 0.05) + 0.25} = 2$$

2. Component B, occuring in one missile 120 times ($m = 120$), may have a probability of failure of "only q'" $= 0.25$ per cent. The required sample size is $N = 60$ units. Cost of procurement of one piece \$1 ($a = 0.001$). Cost of one test \$3 ($b = 0.003$). Cost of test preparation \$500 ($c = 0.5$).

$$PI = \frac{120 \cdot 0.25}{60(0.001 + 0.003) + 0.5} = 40$$

Obviously component type B ought to, and can be, tested with a much higher priority rating than component type A, not only because it produces the enormously high hazard of failure of 30 per cent, but also because it can be manufactured and tested easily and relatively inexpensively.

It cannot be overemphasized that over the years of a reliability test program the majority of the component types need to be tested again and again. Thus the various factors of the priority index will become better and better known. The reliability co-ordinator will thus be able to adapt the test priorities to the changing conditions of the missile development with increasing certainty.

OTHER FACTORS INFLUENCING THE TEST PRIORITIES

The priority index, PI, as well as the hazard of failure, $m \cdot q'$, will not be the only factors for determining the eventual priorities within a reliability test program. Various other factors must be taken into consideration, such as the momentary availability of a certain type of component, or of test facilities, or of test specialists. It may also happen that a component type requires highest priority because it is an essential, yet doubtful, integral part within a very important system.

Therefore, of all the factors involved in determining priorities, the priority index, PI, is intended to serve as <u>the one guiding factor</u> used in the planning process that will provide for acceleration of the growth of the over-all reliability of the missile in the early stages of development.

The hazard of failure, $H = m \cdot q'$, as a guide for priority, is to be preferred in the later stages of developments, where the over-all reliability of the missile must be raised to its highest possible level even though great expense may be involved.

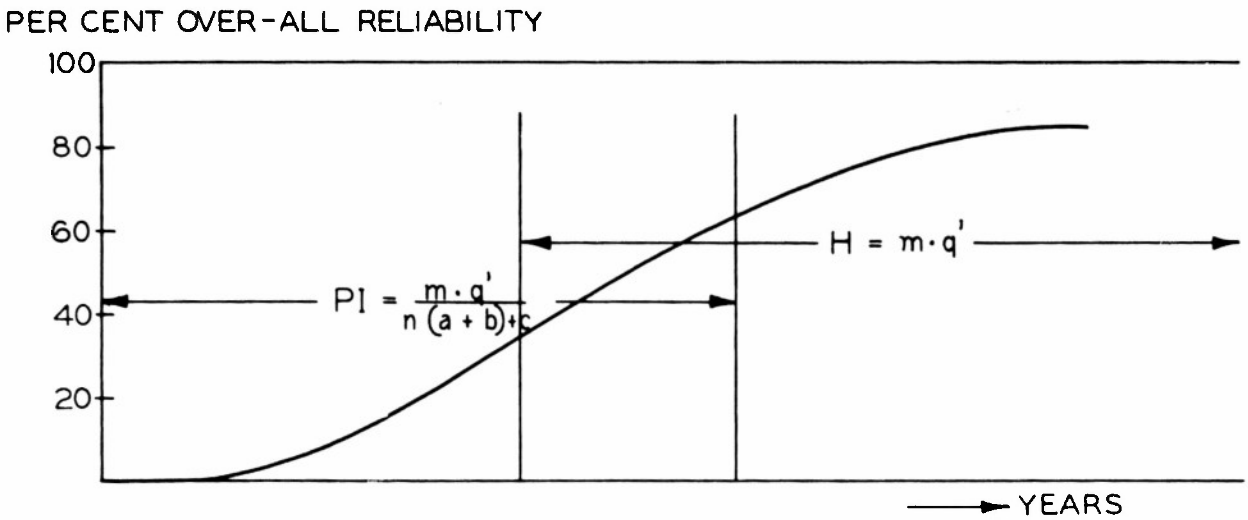

Fig. 7. Periods of Predominant Use of H and PI During a Missile Development.

Figure 7 shows the periods of reliability growth during which each of the two priority scales should be used predominantly. As can be seen, the two periods overlap considerably.

OTHER APPLICATIONS OF THE PRIORITY INDEX

The priority index, PI, is intended to be a tool to be used mainly by the planning reliability co-ordinator and the reliability board. However, some useful secondary consequences may result, such as:

Co-operation Between Designer and Reliability Co-ordinator

In order to further the rapid growth of the over-all reliability it is imperative that designer and reliability co-ordinator co-operate intelligently and thoroughly.

The reliability co-ordinator should indoctrinate the designer with the facts of guided missile reliability and should explain to him the nature and purpose of the priority index. The designer, in turn, must be willing and even anxious to discuss with the reliability co-ordinator the principles of his design and, in particular, the weak spots he may suspect. Mutual understanding along such lines will have two very favorable consequences: First, knowing the nature of the priority index, the designer will avoid undue optimism in estimating the probability of failure, q' of the component he is respo sible for. Second, the influence of the cost of testing, $N(a + b) + c$, on the priority index should induce the designer to co-operate

with the reliability co-ordinator in keeping the expenses for testing as small as possible. The designer will, therefore, not insist, particularly in the first stages of development, on a comprehensive test program that may absorb quite an unreasonable share of the limited test resourcss. Instead he will insist only on testing, and rapidly improving, the most doubtful parts and environments of his component and he will co-operate in finding out how such testing can be furthered most quickly and economically.

Co-operation Between Contractor and Contracting Agency

Reliability test programs will oftentimes require considerable support from the contracting agencies, particularly when severe bottlenecks in procurement and testing cannot be overcome by the limited resources of the contractor. In such cases the priority index submitted to the contracting agency may help with important decisions on such matters as expanding the contract, granting higher priorities, or making available other test resources or research laboratories.

The "Total Hazard" of Failure Produced by a Component Type

Up to now, the hazard of failure, $H = m \cdot q'$, has been used to judge the hazard caused by a component type with regard to only one particular kind of stress or environmental condition. This was called a "test case." Actually, many component types, particularly the sensitive ones, will suffer from several (z) kinds of stresses, for example, shock, vibration, pressure, heat, etc., thus creating z test cases.

Frequently one will want to know the risk to the missile that may be caused by a component type with respect to all environments involved. For this purpose one simply adds up the z individual hazards of failure, and arrives at the "total hazard" of a component type:

$$\begin{aligned} H_{total} &= H_1 + H_2 + H_3 + \cdots\cdots H_z \\ &= m(q_1' + q_2' + q_3' + \cdots\cdots q_z') \end{aligned}$$

This total hazard, H_{total}, will be of considerable value in judging the degree of development a component type has attained. In particular, it will aid in sifting out those component types that require intensified scrutiny and further development, or those that need to be replaced by better types.

Standardization of Guided Missile Components

An increasing number of components especially developed for guided missiles will be used in a variety of missile types. Such components, if they are still unreliable, may require centralized sponsorship. Upon being fully developed, they will be standardized.

In determining the need for such government-sponsored development programs, it may be helpful to use as a scale of priority the "Grand Hazard of Failure," ΣH_{total}, exerted by a component type upon all missile types involved.

If several, or many, such urgent component programs are in competition with one another, and if the testing resources are limited (which is usually the case), it is recommended that a "Grand Priority Index," ΣPI, be used. This will show which of the various programs will probably contribute most rapidly and most effectively to the reliability growth of the entire guided missile develovpnent program.

Thoroughness of Planning Work

One may object to the use of such priority indices on the basis that they are too cumbersome, or lead possibly to overorganization.

The actual calculation of the indices is only a matter of minutes. The real difficulties will arise when the basic values of hazards of failure, $m \cdot q'$, and the various expense factors, $N(a + b) + c$, for the testing, are to be determined. However, for the planning and conducting of a sound and efficient test program, these values must be calculated and collected anyway. This must be considered as one of the main tasks of the reliability co-ordinator.

Widespread application of such planning indices will stimulate, and often enforce, thoroughness in planning work that has as its salient objective the urgently needed rapid growth of the over-all reliability of guided missiles

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PART III

sampling problems

INTRODUCTION

The efficiency of a reliability test program depends greatly on the proper choice of the sample size for each individual test case.

Considerable uncertainty is found in this matter. Some planners have set a goal of 100 units to be tested, whereas others are satisfied with testing only one unit (or, occasionally, none). As a matter of fact, no rules that are generally accepted are available at present.

As shown in Part I, the sampling problem must be considered in the light of the required rapid growth of the over-all reliability.

For this discussion three main categories of components will be distinguished:

1. The standardized component type.
2. The newly developed component type.
3. The isolated prototype.

STANDARDIZED COMPONENT TYPES

Standardized components must, in general, be viewed with suspicion, because most of them were probably developed for less severe environmental conditions and under less severe specifications for reliability than prevail in guided missile applications. In spite of this they have three great advantages over newly developed components:

1. They have already reached a certain degree of perfection.
2. They are comparatively inexpensive.
3. They are immediately available in sufficient numbers for reliability testing and can therefore contribute to the growth of the over-all reliability much sooner than other components.

Standardized components can therefore be considered as a great asset in the reliability development of a guided missile and it would be ideal if one could build a new missile type mainly, or entirely, with standarized components. Such an ideal opportunity will of course never occur. It is highly desirable, however, that in the not-too-distant future a growing number of typical guided missile components will become standardized, with well-known, very high "strengths."*

*See NAMTC Technical Reports Nos. 75 and 84.

The Priority Index, $PI = \frac{m \cdot q'}{N(a + b) + c}$, discussed in Part II, indicates clearly that most of the standardized components should be selected as the first subjects for reliability testing, because they occur most frequently in a missile, are relatively inexpensive, and are readily available for testing.

There is another reason for urgency in the testing of standardized components: Because they originate in mass production processes that are exceedingly well-tooled-up and inflexible, even minor changes in design may cause severe disturbances in the production process. The general reluctance of manufacturers to agree with such changes is understandable; however, severe setbacks and delays in the growth of the over-all reliability of the missile will result if necessary modifications are delayed.

All of these reasons indicate that the reliability testing of the standardized components should be started without delay.

This is true even if, in the early stages of a missile development, the severity of some of the environmental conditions is known only vaguely, or not at all. In the interest of rapid growth of the over-all reliability it is highly desirable to reveal, as early as feasible, the weakest spots of a component type (see figure 8).

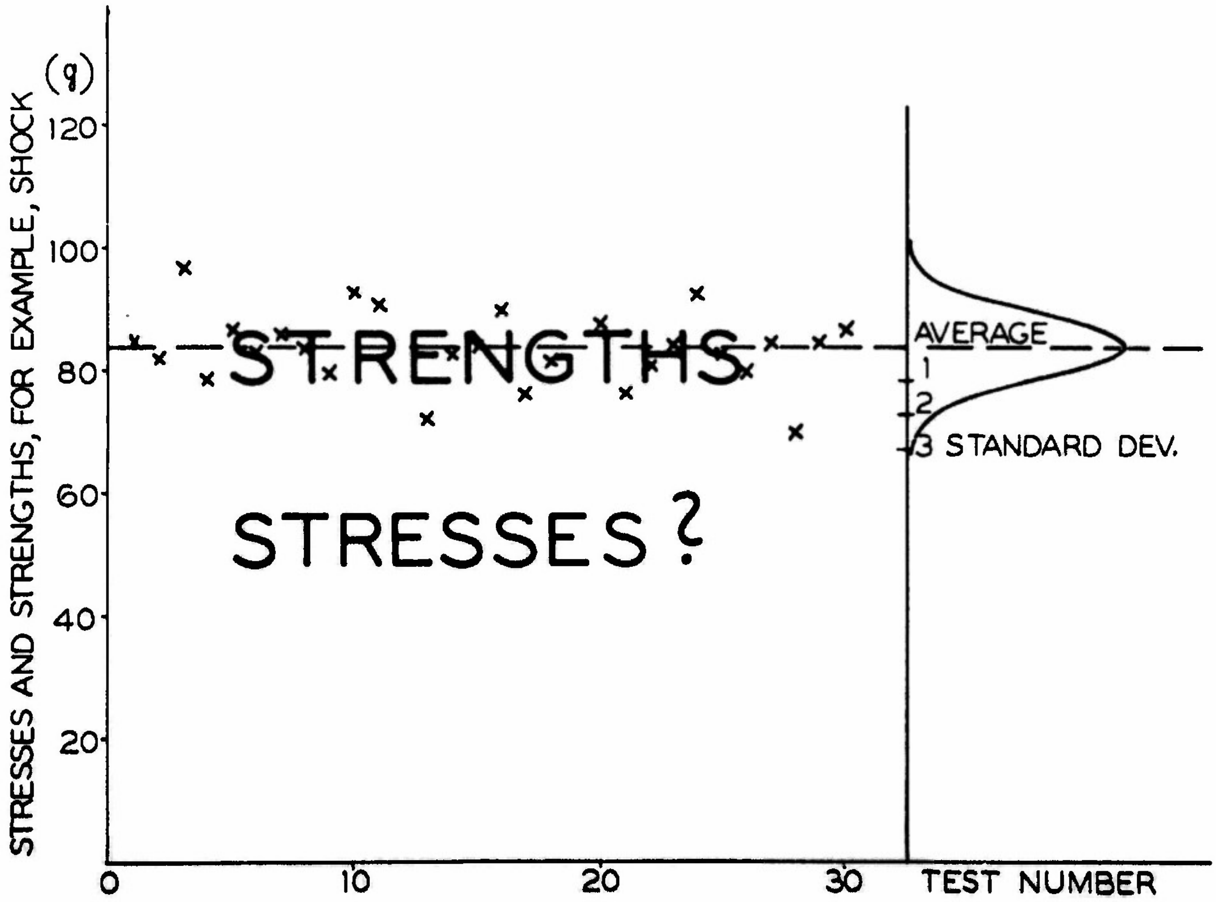

Fig. 8. Scatterband of Strengths of a Component Type.

As soon as the stresses are also determined, for example, by flight testing dummy missiles, one will be able to judge without further delay whether such a "weak spot" is acceptable or whether serious changes in design and in interferences in the mass production process are unavoidably required.

The early knowledge of the weak spots of standardized components may, in turn, lead to the decision that a critical environmental stress must be reduced at high priority, and the standardized component left unchanged.

Oftentimes, when such "environment testing" results in objectionable delay, it is necessary that the reliability board estimate and specify preliminarily the maximum stresses or environments to which a component will probably be subjected in transportation, storage, and service. Such an estimate is very helpful as a modus operandi for judging, and eliminating, the most obvious weaknesses of a component type as revealed by the first tests-to-failure. As soon as the environments become better known, quick action should be taken to modify the component accordingly or to reduce the severity of environment, if feasible.

"BEST" SAMPLE SIZES FOR STANDARDIZED COMPONENTS

With regard to the accuracy of a statistical evaluation, 100 test units are preferable to 25, and 25 are preferable to 5, of course. One must realize, however, that in the first 1 or 2 years of missile development a very rapid growth of the over-all reliability should be striven for. In that early stage, statistical accuracy is of minor importance because, in any event, the components need to be modified step by step until they are satisfactorily adapted and reliable. In the later stages, and in particular shortly before mass production is to be ordered, considerable emphasis should be laid on statistical accuracy, which will necessitate an increase in sample sizes.

No rule of thumb for determining the "best" sample size can be given because each of the hundreds of test cases must be studied individually, and because considerable engineering judgment is required in reaching a decision.

Some general rules, however, can be derived by again consulting the formula for the Priority Index, $PI = \frac{m \cdot q}{N(a + b) + c}$.

As a first approach the sample size should be so chosen that a fairly reliable statistical result can be expected, for example, $n = 20$ or 25. This tentative sample size may then be modified step by step by the following considerations:

1. If the expense of procuring and testing a unit, $(a + b)$, is small compared to the expense, c, of preparing that particular test program, the initially chosen sample size should be increased, and vice versa.

After the "best" sample size, N, has been determined, the ultimate Priority Index, PI, can be determined for each test case. The various "components", (i.e., test cases) are then to be listed in the sequence of their Priority Indices, and those with the largest indices heing put first. Such a list will help to determine the ultimate test priorities, as described on page 18.

NEWLY DEVELOPED COMPONENTS

As discussed in Part I, the early stages of a reliability test program will exert the strongest influence on the success or failure of a flight test program, and of the entire missile weapon as well. Unfortunately the number of units produced at those early stages will oftentimes be too small for a proper statistical evaluation of the test results.

In such cases of initial scarcity, the rules for determining the best sample size should he used, at least hypothetically and temporarily, to arrive at Priority Indices that emphasize the "weight" of the various "test cases" for the reliability test program. There will be many cases for which PI turns out to be very high. <u>Every effort should then be made to produce the required number of test units as quickly as feasible.</u>

THE PROTOTYPE UNIT

Oftentimes only one unit of a component type will exist. With a single unit no reliability test program can of course be conducted. However, in the interest of the rapid growth of the over-all reliability, such a component must be tested as soon as feasible, in order to find its most critical weaknesses, at least tentatively and preliminarily. It would be inexcusable to postpone a critical test case until more units are available. <u>Testing of one unit is immensely preferable to no testing at all!</u> Thus the first prototype unit represents the most valuable unit for the whole reliability test program, even if it does not exhibit the final configuration. Consequently a prototype unit should never be expended in a flight test missile. Such misuse may in many cases not only cause an expensive missile to fail, but may also delay the growth of reliability by the time interval required to produce a second unit for the test.

It should be stated here that nonavailahility of a component for reliability testing must, in many cases, he considered as an indication of poor judgment and organization. This holds particularly true when such a component type is going to be used in expensive flight test missiles.

A designer may be reluctant to permit his prototype to be tested to failure, i.e., to permit it to be destroyed. Such reluctance may occasionly be justified, hut not in the majority of the cases. As a general rule, a second and third unit should be at hand for the failure testing immediately after the system testing of the prototype has more or less proved its adequacy for the design purposes.*

*Subcontractors who have not as yet been concerned with guided missile components, and who are therefore unaware of the difficult reliability problem, will most probably object to such haste. To secure the intelligent co-operation of the subcontractors, it is imperative that they be sufficiently indoctrinated. This indoctrination is an important task of the reliability co-ordinator.

OBTAINING MAXIMUM INFORMATION FROM AN ISOLATED (PROTOTYPE) UNIT

Single Environmental Condition

Fortunately most of the components of a guided missile actually suffer from only one kind of stress or environmental condition. In such cases it is necessary to concentrate on the part or location (e.g., cross section) which, under increasingly severe stress will always fail first.

If the first test proves that the "strength" is very much above the maximum stress (for example, three times as high or higher), testing may be discontinued preliminarily, and even permanently in cases of extreme strength.

If the first test reveals a strength close to the maximum stress, more units must immediately be ordered for continuing the tests. These subsequent units, however, should be reinforced, or otherwise improved, before continuing with the testing. In all such cases one should see whether the maximum stress or environmental condition can be greatly reduced.* Such reduction is of particular value because, in many instances, not only one component but many components will be improved relatively, i.e., become more reliable without modification.

Multiple Independent Environmental Conditions

For components that are being subjected to several independent environmental conditions, one must try to anticipate, before testing, which conditions may be the most adverse. The next step is to find out which of the tests are the least destructive. These tests should be made first, if they are not too time consuming.

Example: A component may be subjected to:

1. Shock (destructive)
2. Cold (nondestructive)
3. Vibration (very destructive)
4. Dust (nondestructive)

For obtaining maximum information from the one prototype unit, the test program should be conducted in the sequence:

1. Dust (nondestructive)
2. Cold (nondestructive)
4. Shock (destructive)
4. Vibration (very destructive)

*See NAMTC Technical Report No. 75, page 33, point 4.

After the tests one will know much better which of the environments are really impairing the reliability, and which are harmless. After the predominant causes of failures have been detected, the testing should be concentrated on those critical environmental conditions

If the prototype is destroyed, for example, by shock, one will try to repair it for use in the destructive vibration test. It may even be feasible to repair a component repeatedly before it becomes entirely useless for further testing. Before repair eventually becomes impossible, more units must be quickly produced.

By this method one can rapidly discover the weakest parts, or properties, of a component type, even though only one unit is available. A large proportion of components can thus be improved in the first stages of their development.

The test results obtained in this manner are of course not the basis for judging the reliability conclusively, nor for far-reaching decisions, such as the ordering of mass production of a component type. The reliability testing must be resumed as soon as more units become available for testing. In the meantime one should try to increase his knowledge of the environmental conditions in order to provide a basis for evaluating the reliability.

Multiple Interdependent Environmental Conditions

This problem was discussed in NAMTC Techincal Report No. 84. The most significant conclusions are reprinted here:

> "With increasing numbers of interacting critical conditions, it will become increasingly difficult, time-consuming, and costly to test the significant stress-strength combinations and to evaluate their probability of failure. Such cases may indicate that the component in question is so complex that it has but little chance of becoming serviceable in time. Insufficient response to testing methods should be considered as a strong indication of not only great immaturity, but faulty development as well."

> "In this connection it cannot be too strongly emphasized that complex components which are difficult to evaluate and to develop by ground-testing are by far more difficult or even impossible to develop to reliability by flight-testing."

Testing of components under multiple interdependent environments will require considerably larger numbers of test units than the more simple cases discussed in the two preceding sections, i.e., single environmental condition and multiple independent environmental conditions. The volume and complexity of testing will also be considerably larger. For these

reasons most of the newly developed very complex components can be tested for reliability only after the later stages of the development are reached. As a consequence the newly developed complex components will always represent the worst liabilities of a missile development. One such component, or system can easily prevent the success of a guided missile type. Great caution and skepticism are therefore required in estimating the chances of making such components mature and reliable in due time. In many cases it may be advisable to develop a second, or even a third, solution simultaneously.

The best method for avoiding such liabilities, however, lies in striving for utmost simplicity in design.

In this connection it should be pointed out that the testing of components (or complete missiles) under multiple environmental conditions can be greatly expedited by proper test planning. It would be very desirable to have the aid of a good statistician, well versed in the analysis of variance, in regression, and in other methods of increasing the efficiency and significance of the test process.

PREFLIGHT TESTING OF COMPLETE FLIGHT TEST MISSILES

In the preceding chapters the problem of testing and sampling of guided missile components is discussed from the standpoint of how readily the various component types are available for testing, how easily they can be tested "up to failure," and how weak and doubtful they are.

According to the concepts advocated in NAMTC Technical Reports No. 75 and No. 84, all components that may be critical to a guided missile type should be subjected to the important, or critical environmental conditions, but at intensities several times more severe than in service, in order to find out at what intensity the device will fail, i.e., "the ultimate strength." The safety margin between service loading and failure loading is then examined to see whether such safety margins are adequate in view of the variability of service conditions and reproducibility of the component in question.

The importance of this philosophy will increase, the more closely the critical phase of early mass production is approached. At that stage one must know numerically what the service environments really are and what severity of stresses the various components are capable of sustaining without failure. No component type should go into mass production that is still marginal and hazardous to the missile weapon.

There is, however, another very important aspect of the reliability problem: How shall one handle a complete test missile that consists of many components, the individual reliabilities of which are, at that stage, unknown? Shall such a test missile be withheld from firing until all or

most of the pertinent up-to-failure tests have been satisfactorily completed? Or should the manifold risk of a failure of such an expensive test missile be taken?

There are two alternatives to be considered. Assuming first, that only one particular doubtful component is to be used in the firing of a fully developed missile, should the risk of a missile failure not be taken just because that weak component will possibly fail?

In this case one might be satisfied with the evidence that the component in question shows a high probability of surviving this test flight. It is not necessary to ground test any other unit but this one, nor is it necessary to test it up to failure and possibly to destruction. It will frequently suffice to test it up to a severity of the most critical condition (or conditions) that is well above the condition of flight.* Whether optimism or pessimism is the proper attitude in such a case depends largely on the particular situation produced by many circumstances such as the doubtfulness of the component in question, the cost of the missile, the urgency of the firing within the schedules of the development, the availability of more missiles for continuing the test, the program importance of the particular missile type, etc.

The second alternative is the case of a test missile that may contain not only one, or two, but a great many doubtful components. In such cases, particularly if the missile is expensive, the decision whether the missile should or should not be fired is very difficult to make.

The most logical method seems to be to subject the whole test missile to the specified environmental "test values" and to prevent the firing of missiles that fail, until an assembly that will pass the test schedule is forthcoming.

"Undertesting" and "overtesting" are two serious risks encountered in the use of this method. Undertesting, i.e., testing at conditions milder than those occuring in flight, does not help to detect all of the "weak" components, and may therefore result in failure of the missile. Overtesting, i.e., testing at too severe conditions or for too long a time, may bring one, or many, components to the verge of failure and thus cause the very missile failure that should have been prevented by the test method.

Whether a given test condition is too mild or too severe is very difficult to decide. Depending on the background, attitude, and interest of many people, each concerned with the survival of their particular component, opinions about what test severity would constitute the "best" compromise will always differ greatly. This situation is made even more

*This statement is not incompatible with the concepts discussed in Chapter 5. It is of course highly preferable and reassuring to know (from up-to-failure testing) the maximum strength of a component type before the missile is to be fired. Occasionally this up-to-failure testing is not feasible and oftentimes too late recognized as being necessary.

difficult by the fact that not one but several environmental conditions must be considered, and these conditions are frequently interdependent and often only vaguely known.

Thus the latitude between the risks of undertesting and overtesting a missile may often be rather small. Consequently, the responsibility for taking the risk of a "very doubtful" (and possibly very expensive) test firing is largely shifted from the designers and manufacturers to those persons who must ultimately specify the severities of the various kinds of environmental preflight tests. These persons may often be put in a rather difficult position.

Nevertheless it would be highly desirable to develop rational environmental test methods for complete missiles, in order to expedite flight test programs. The discussion of this problem, however, does not lie within the scope of this study.

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PART IV

problems of organization

GENERAL

The reliability of any ordinary complex technical apparatus (automobiles, aircraft, etc.) must essentially be designed into it. However, the final growth of the reliability to the required level can be accomplished only by testing a great many units under service conditions and by current statistical evaluation of the failures that occur during actual service use. Inadequacies and failures are ordinarily detected quickly and are easily traced to their basic cause, and this leads to their elimination as potential hazards. Thus one can say that, paradoxic as it seems, failures are essential and instrumental to the achievement of the ultimate level of reliability.

Unfortunately the reliability of guided missiles can rarely profit from failures in flight testing and service use because it is very difficult to trace failures in flight to their basic causes and origins. In one evaluation of a considerable number of failures of flight test missiles, it was found that, on the average, the cause of a failure in flight can be traced not much further than to the system (guidance, propulsion, airframe, etc.) that by its malfunction, has caused the missile to fail. The statistical evaluation of the "Efficiency of Tracing" of the causes of these flight failures is very significant. In a particular study of this point it was found that:

8 per cent could not be traced at all.
44 per cent could be traced to the system.
28 per cent could be traced to the component.
14 per cent could be traced to the element.
6 per cent could be traced to the basic cause.

Thus only 6 per cent of the failures in flight led to the elimination of the responsible "ailments" of the missile type.

Even if one assumes that the techniques for tracing the causes of flight failures will steadily be improved, one should realize that failures of guided missiles in flight can never produce sufficient information to bring about the urgently needed growth of the over-all reliability. Other methods and means must be developed instead, such as comprehensive scrutiny of all component types involved and by testing these components "up to failure" in order to reveal their maximum strengths and their safety margins relative to all environmental conditions.

As discussed in Part I, this is a task of great difficulty and extreme responsibility. To accomplish it satisfactorily it is necessary that all conceivable methods and means of organization that may help to further the growth or reliability be thoroughly studied and freely applied.

The author realizes that, at the present, discussion of these matters is highly controversial. However, the precariousness of the reliability situation of guided missiles demands that not only the theoretical but also the organizational problems be attacked without delay. As the scope of experience enlarges, these concepts of organization will be improved, or replaced by better ones, until firm ground is reached.

MEANS OF HANDLING RELIABILITY DATA

The List of Components

The first step in a reliability test program consists of preparing and keeping a complete and very detailed list of all the component types that could become hazards to the missile.

It is customary to build up such component lists as the development of a missile is progressing. However, these lists come, in general, much too late for the requirements of a reliability co-ordinator, who should always keep abreast of, or preferably be ahead of, a missile development, as far as reliability is concerned. Moreover such lists are not set up to contain the specific information necessary in the scrutiny of the reliability of a guided missile.

A suggestion for a component list is shown in Table 1:

LIST OF COMPONENTS

MISSILE TYPE: WASP II
SYSTEM: POWER SUPPLY

POS. NO.	UNITS PER MISSILE	COMPONENT TYPE ORIGINATING FIRM	EXPERTS	UNITS AVAILABLE FOR TESTS	UNITS ON ORDER	DATE OF DELIVERY	REMARKS	URGENCY OF TESTING
1	25	AMPLIFIER, TYPE X-5 GRIDLEY, BOSTON	SMITH JONES	5	20	3/15/52	NO RELIABILITY TESTS PERFORMED CONFERENCE 2/5/52	XXX
2	1	MASTERSWITCH R/6 WESTINGHOUSE	SMITH MILLER	1	15	4/28/52	RELIABILITY DATA REQUESTED FROM VENDOR LETTER 1/14/52	X

Among the various items to be listed, the names of experts deserve particular attention. From the very beginning of a development, the reliability co-ordinator should attempt to learn the names of the foremost men and specialists, of his own firm as well as those of the originating firm, who can and are willing to co-operate with him in the matter of reliability. Close personal contact between the reliability co-ordinator and these experts in design, production, and quality control is essential if delays in the growth of reliability are to be avoided. Such delays might easily accumulate to years.

These specialists should be indoctrinated as soon as feasible in matters of reliability peculiar to guided missiles. This again is a very specific task of the reliability co-ordinator.

The List of Stresses and Environmental Conditions

At the beginning of a development most of the main stresses and environmental conditions can be anticipated only vaguely. However, to provide a basis for an early appraisal of the standardized components to be used and a basis for the development of new components, one ought to determine the most important stresses and conditions tentatively, preliminarily, and conservatively. Such prognostication must be done by the specialists responsible for the various fields of design and by those responsible for the specifications.

To avoid undue optimism, it is essential that these specialists become well acquainted with the precarious reliability situation of guided missiles.

The importance of such preliminary specifications for the reliability progress of a guided missile cannot be overemphasized. They should therefore be under the control of the Reliability Board.*

As the development progresses, the environments will become better known and the list will need to be revised step by step.

Such clerical work, however, is not all that should be done by the reliability co-ordinator. Whenever a stress or condition is found to be more severe than anticipated, or whenever a new kind of stress or environmental condition is detected (such setbacks are unavoidable), the relative reliability of some, occasionally of hundreds, of components may be critically lowered. It is very much in the interest of the rapid growth of the over-all reliability that quick action should be taken, such as: the relaying of new facts to all internal and external activities involved, discussion of the technical and contractual requirements for adapting a component type to the new condition, planning of the procurement of improved units for reliability testing and flight testing, and supervising the new schedules of delivery.

*See discussions on Reliability Board in NAMTC Technical Reports Nos. 75 and 84.

Such actions of co-ordination require a superior insight into the present and future reliability situation of the missile, a strong sense of responsibility, a considerable organizational ability and initiative, and close personal contact with all specialists of development and all reliability co-ordinators at the vendors' establishments. The reliability co-ordinator is expected to possess all of these qualifications. It is recommended that he and his staff* be charged with this organizational task.

The "Plan of Survey."

By combining the "List of Components" with the "List of Stresses and Environments" a clear view of the many hazards to the missile is achieved. These hazards can best be presented (Table 2) in the form of a "Plan of Survey." as suggested in NAMTC Technical Report No. 75.

Such a plan will be particularly useful at the beginning of a missile development. At that time a tentative and preliminary distinction should be made between combinations that are possibly critical (XXX), important (XX), to be considered (X), or not involved (-).

The Card File of Hazards

In the later stages of a missile development, more highly detailed data will be required for scrutiny and for planning and conducting a reliability test program. For this purpose a "Card File of Hazards" is suggested. Here one should find all essential data for each component type, such as:

1. Origin of design; name of firm and expert designer.
2. Manufacturer; names of expert for production, and of inspector.
3. All critical stresses and environmental conditions.
4. Safety margins; specified, K
5. Safety margins; attained, k.
6. Index of probability of failure, q'.
7. Frequency of occurence in the missile, m.
8. Hazard of failure, m·q'.
9. Number of test units, N, required at various stages of the program.
10. Cost for one unit (a).
11. Cost of one test (b).
12. Cost for preparing the test (c).
13. Priority Index, PI.
14. Test Priority.
15. Test activity; name of laboratory and of responsible person.
16. Date of beginning of tests.
17. Date of completion of tests.
18. State of development (survey, maturity).
19. State of production.

*The organization of the reliability staff will be discussed later in this study.

TABLE II

SAMPLE FORM OF A "PLAN OF SURVEY" (REPRINTED FROM NAMTC TECHNICAL REPORT NO. 75.)

Pos. No.	SYSTEMS AND COMPONENTS	A. MOST ADVERSE CONDITIONS ON THE GROUND							B. MOST ADVERSE CONDITIONS DURING LAUNCHING						C. MOST ADVERSE CONDITIONS DURING FLIGHT					
		TRANSPORT AND HANDLING	HEAT AND COLD	MOISTURE AND CORROSION	DUST AND DIRT	DECAY	FIELD ASSEMBLY AND ADJUSTM'T	OTHERS	LONGITUDINAL SHOCKS	TRANSVERSAL SHOCKS	SUDDENLY APPLIED LOAD	ENGINE IGNITION SHOCKS	OTHERS		NORMAL & LATERAL ACCELERATION	ENGINE VIBRATION	OVER-HEATING	FORMATION OF ICE	OTHERS	REMARKS
A	AIRFRAME	1	2	3	4	5	6	7	1	2	3	4	5	6	1	2	3	4	5	
1	Wings	X	-	X	-	-	XX		XX	X	X	-			XX	-	-	XX		
2	Spar	XX	-	-	-	-	X		XX	X	XX	-			XX	-	-	-		
3	Fuselage: Nose Cone	X	-	X	-	-	X		-	-	-	-			-	-	-	-		
4	Center Part	-	-	-	-	-	X		XX	X	-	-			-	-	-	X		
5	End Part	-	-	X	-	-	XX		XX	-	-	-			-	XX	-	-		
6	Tow Hook	-	-	-	-	-	XX		XXX	X	XX	-				-				
7	Empennage: Stabilizer	X	-	-	-	-	X		X	X	X	-			X	X	-	X		
8	Fin	X	-	-	-	-	X		X	X	X	-			XX	XX	X	X		
9	Etc.																			
B	AUTOPILOT																			
1	Displacement Gyro	XX	XX	XX	-	-	-		XXX	X	X	X			-	XX	-	-		
2	Two Rate Gyros	XX	XX	XX	-	-	-		XXX	X	X	X			-	XX	-	-		
3	Coupling Mechanism	-	X	X	X	-	-		X	X	-	X			-	X	-	-		
4	Two Damping Bellows	-	-	-	-	-	-		X	X	-	X			-	XXX	-	-		
5	Two Servomotors	-	XX	X	-	-	-		X	X	-	X			X	XX	-	-		
6	Air hoses, &. connections	-	XX	-	-	XXX	XXX		-	-	-	-			-	XX	-	-		
7	Erection System	X	X	X	X	-	-		X	X	X	X				XXX		XX		
8	Etc.																			
C	PROPULSION																			
1	Engine Flapper Valves	-	--	X	-	-	-		-	-	-	-			-	XXX	XXX	-		
2	Fuel Pressure Regulator	X	-	X	XX	-	XXX		-	-	-	X			-	XX	-	-		
3	One Way Valve	-	-	X	X	-	-		-	-	-	-			-	-	-	-		
4	Engine Tube	-	-	-	-	-	-		X	-	-	-			-	XX	XX	-		
5	Gasoline Tank	-	-	XX	-	-	-		-	XX	-	-			-	-	-	-		
6	Etc.																			
D	ELECTRONIC EQUIPMENT																			
1	Battery	-	X	-		XXX	XXX		XX	X	-	-			-	X	-	-		
2	Etc.																			

The preliminary signs (X = to be considered; XX = important; XXX = possibly critical; (-) = not involved) are to be replaced by actual data as the test program proceeds.

Depending on the complexity of a component and on the number of critical environmental conditions, each component type will require several, or many, subcards. The file of a complex missile will therefore grow quite large; consequently, all means should be used to emphasize and bring to attention the most critical hazards, (i.e., through the use of file tabs of various colors)

List of Test Results and the Reliability Chart

As a reliability test program grows it will yield the reliability data of an increasing number of component types relative to the various critical conditions. Such data are:

1. The "reliability index," p'*.
2. The "hazard of failure," $H = m \cdot q'$** (relative to one particular condition).
3. The "total hazard of failure," $H_{total} = m \cdot q'$ (relative to all critical conditions involved).

A separate list should be kept for each of the main systems. This list should include all components of the system and should show the data*** mentioned in the preceding section.

The purpose of these system lists is to bring out as early as possible, the total hazard of failure generated by each of the systems, and by each individual component type within a system, and to help to decide which systems need intensified development and which should, as soon as possible, be replaced by better systems or types.

As these lists become more and more extensive and complete, the reliability co-ordinator will carry over the hazards, $m \cdot q'$, on to a master list, in the order of their magnitude, and plot the data from the lists in one of the "Reliability Charts" suggested in NAMTC Technical Report No. 75, Part III. Thus, pictures of the over-all reliability situation of the current stages of development will be available that will show, for example:

The total number of scrutinized components and conditions.
The number of doubtful components that have not yet been tested or evaluated for reliability.
The number of "erratic" components.
The index of the over-all reliability.

*Discussed in NAMTC Technical Report No. 84, page 46.

**Discussed on page 16.

*** See NAMTC Technical Report No. 75, List II, page 60.

The "Poster of Erratics"

As a reliability test program gets under way, more and more combinations of components and environments will be revealed as particularly hazardous to the missile. Such combinations, outlined in NAMTC Technical Peport No. 75, may be called "Erratic." These should be strongly emphasized, not only in the card file and in the lists, but also on a special "Poster of Erratics," set up in the office of the reliability co-ordinator.

These posters should show at a glance the most critical hazards and the most pertinent data, such as the probability of failure, q'; the frequency of occurrence, m; the hazard of failure, $m \cdot q'$; the total hazard of failure, $\Sigma m \cdot q'$; schedules for further testing; severe bottlenecks; etc.

As some of these critical difficulties are overcome, their listings can be omitted from the poster of erratics. New cases will occur that need to be posted. Thus, for the sake of flexibility, one could write the essential data on separate paoer inserts that could easily be changed or removed. Various colors would help to emphasize the most critical items.

Such a poster, by its mere existence, will emphasize the most alarming hazards and stimulate action on the part of those concerned.

ESTABLISHMENT OF A RELIABILITY GROUP

Offhand consideration may lead to the assumption that the development of the reliability of guided missiles belongs essentially in the realm of the well-established organization of inspection and quality control and that therefore a separate organization for taking care of the reliability would not be necessary. That this is not true can be seen by considering the specific tasks of the reliability group, as conceived in this study:

1. Making preliminary estimates concerning a new guided missile project, with reference to the over-all reliability achievable.
2. Indoctrinating all designers and research workers, within and outside the plant, concerning facts, methods, and tools for achieving reliability.
3. Improving existing methods and tools and developing new ones for achieving high reliability.
4. Establishing a rigid scrutiny of all conceivable hazards of failure by keeping and evaluating lists, tables, charts, etc.
5. Initiating, supervising, and evaluating reliability tests that are necessary for sifting out, improving, or rejecting unreliable component types.
6. Planning and supervising the study (with the aid of experts in all fields concerned) of all stresses and environmental conditions that may impair reliability.
7. Planning and supervising the study (with the aid of experts in all fields concerned) of the specifications, in particular of the safety margins that are to be specified, and revised.

8. Keeping close personal contact with all vendors in order to secure an adequately high reliability in all their designs.

9. Keeping close personal contact with the organizations of quality control, flight testing, logistics, and field operations, for the purpose of collecting all available facts about doubtful components and conditions that need to be scrutinized.

10. Determining the Priority Indices for test programs.

11. Indoctrinating military instructors.

12. Supervising and evaluating all logistics <u>with regard to reliability.</u>

13. Co-operating with the fleet during troop training and service use, for detecting and evaluating more hazards and failures; co-operating in the writing of RUDM's (Reports of Unsatisfactory or Defective Material); and in initiating quick action for retesting, improvements, or rejection.*

The reader may judge for himself which of these tasks could be taken over by the organizations of inspection and of statistical quality control as they now exist within the firms.

The organizational problem may be further clarified by the following considerations:

1. One of the main objectives of statistical quality control is the finding of an optimum compromise between <u>quality</u> on the one hand and <u>cost</u> of production, inspection, repair, or rejection on the other hand. Such compromises vary greatly from case to case, yet <u>their order of magnitude</u> is illustrated by typical specifications like this: "A lot is accepted if the sample does not contain more than 1 (or 2, or 3) per cent defectives."

Such scales of "quality" have proved to be quite satisfactory for practically all fields of technique - except guided missiles. For guided missiles they are not only inadequate but even ruinous, because of the known "links-of-a-chain" character of the operation of components in a missile, and because missiles are not recoverable for postflight inspection.

This situation may be illustrated by two hypothetical examples:

<u>In an aircraft</u>, the receiver ceases to operate. The cause, failure of a vacuum tube, will immediately be recognized by the crew. After the aircraft has landed, the basic cause, within the tube, can be determined with certaintity by the ground crew. Replacement of the tube may take a few minutes and may cost a few dollars. After replacement of the tube, the aircraft receiver is perfectly operable again.

*It is obvious that the reliability group has to perform many typical tasks of "co-ordination": co-ordination of stresses, safety margins, and strengths for all components and environments; co-ordination of research engineers, designers, manufacturers, operators, with respect to reliability; co-ordination of contracting agencies, contractors, subcontractors, with respect to reliability; co-ordination of test priorities; co-ordination of the probabilities of failure of all components (scrutiny).

Consequently the title of "Reliability <u>Co-ordinator</u>" seems to be not only appropriate but necessary to designate those whose job it is to perform such difficult and thankless tasks.

In a guided missile, the failure of a vacuum tube will unavoidably cause the loss of an entire "firing" which, including all operational expenses, may represent a loss of $100,000 or more and may possibly mean penetration by an enemy bomber with catastrophic consequences. To make things worse, it is probably almost impossible in flight to identify the tube as the real cause of the missile failure, let alone to diagnose the basic cause of the failure within the tube. Such diagonsis, however, is indespensable as a basis for the prevention of future missile failures from the same cause.

It may be a long time before such bitter facts are thoroughly recognized and appreciated by all those concerned with the development, manufacturing, and operation of guided missiles and their components.

2. The advocates of modern quality control frequently complain that the principles of quality control are fully appreciated and applied only by the larger and more quality-conscious firms. For instance, the Niagara Frontier Division of Bell Aircraft Corporation analyzed acceptance and rejection records covering nearly 35 million parts purchased from 458 companies.* Only 1.95 per cent of these parts were found defective and rejected. But it was found that:

277 companies supplied parts 0 to 1.99 per cent defective.
39 companies supplied parts 2 to 4,99 per cent defective.
31 companies supplied parts 5 to 9.99 per cent defective.
44 companies supplied parts 10 to 19.99 per cent defective.
36 companies supplied parts 20 to 49.99 per cent defective.
31 companees supplied parts 50 to 100 per cent defective.

One can hope that this unsatisfactory situation has improved since 1944; however, it certainly can not have improved to such a degree that the much more rigid requirements of guided missiles are met. It cannot be over-emphasized that in all "normal" fields of technique (e.g., aircraft, automobiles) the final perfection in quality is achieved mainly by experience in testing under service conditions, and by experience in actual service. Such experience results in many RUDM's (Reports of Unsatisfactory and Defective Material). In contrast, the reliability of a guided missile type must essentially be achieved through design and through comprehensive reliability testing of all components, even before the missile is subjected to flight testing, and long before statistical quality control in mass production becomes active and effective.

3. It is also said that the indoctrination of designers in the principles of statistical quality control is slow, oftentimes much too slow. Thus, it cannot be expected that all of the many designers, manufacturers, and even inspectors, involved in the design, production, and quality control of guided missile components could, at the present time, have acquired the

*Chese, Herbert, "Bell Puts Teeth Into Quality Control," Wings, vol.3, pp. 1181-1185, September, 1944. Quoted from E.L. Grent, Statistical Quality Control, McGraw-Hill Book Co., Inc., 1946.

much more rigorous criteria of component reliability testing that are indispensible to the creation of a reliable guided missile.

One comes to the conclusion that a separate organization, the reliability group, must be called into being. Such a group can see the many hundreds of intricate problems occurring in specifications, environments, design, manufacturing, and operation, primarily in the light of the over-all reliability.

Whereas the quality control group centers its activities within the production branch, the activities of the reliability group will be centered within the organization of development (i.e., research, design, testing). Like many quality control groups, however, the reliability group should be made responsible to "top" management only. The reliability co-ordinator should be on a par with the production superintendent, chief engineer, etc.

Obviously the tasks of the quality control and reliability groups are complementary and their activities overlap to a certain extent. It is therefore necessary that the two groups co-operate fully with each other.

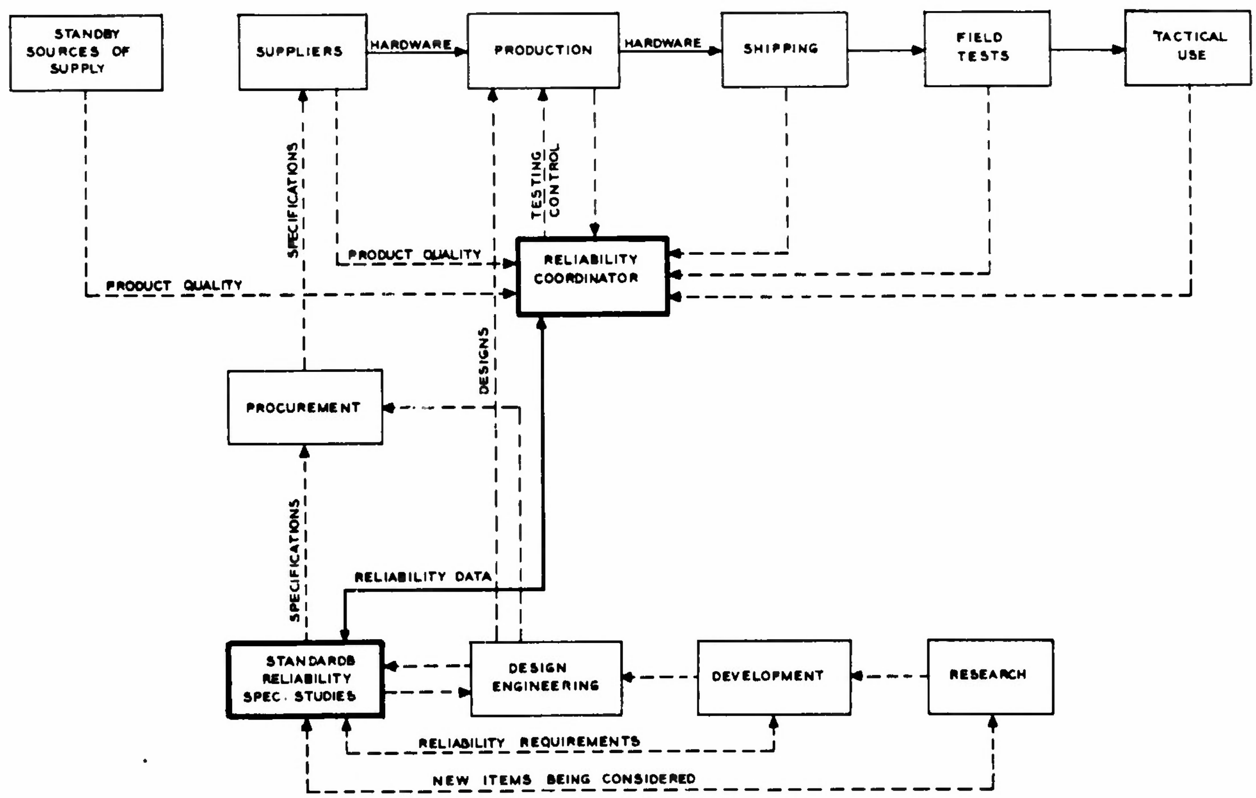

Fig. 9. Typical Organization for Reliability Control.

Recently an increasing number of organizational block diagrams, devised by various activities, have shown the important role of the reliability group in relation to the organizations of development and production. One excellent example , designed by William T. Sumerlin,* are reprinted here without further discussion. (See figure 9)

COMPOSITION OF A RELIABILITY GROUP

From the many different tasks listed earlier in this part of the report, it is obvious that one reliability co-ordinator alone simply cannot perform such an enormously complex and responsible job. He will require a staff of at least one specialist in each of the principal fields of guided missile technique, such as:

1. Preliminary design.
2. Specifications.
3. Airframe design and stress analysis.
4. Propulsion.
5. Electronics.
6. Hydraulics.
7. Control system.
8. Guidance.
9. Testing methods.
10. Production.
11. Statistics.
12. Quality Control.
13. Logistics.
14. Troop training.
15. Operational analysis.

These specialists will form the Reliability Co-ordination Group, or simply the Reliability Group, located in the firm of the main contractor.

The subcontractors will need a similar, although smaller, reliability group for achieving the required high reliability of their products before they are sent to the main contractor. This will help in securing full understanding and maximum support wherever the reliability of guided missiles is at stake.

REQUIRED QUALIFICATIONS FOR THE MEMBERS OF THE RELIABILITY GROUP

To obtain the highest efficiency and best results from such a reliability group it is essential that each representative have the following background and ability:

1. He must be an expert and up to date in the entire field of his specialty, including theory, design, manufacturing, operation, etc., and must assume the responsibility for the co-ordination of reliability problems.

*Sumerlin, William T., Philco Corporation, Philadelphia, Pa. "Application Engineering for Improved Electronic Reliability in Guided Missiles." Paper presented at the 1952 I.R.E. National Convention New York, N.Y., 6 March 1952.

2. He must be thoroughly familiar with the concepts of statistical quality control and with the concepts of reliability control peculiar to guided missiles.

3. He must not only be strongly convinced of the importance, urgency, and responsibility of his task, but must act accordingly.

4. He must have enthusiasm for his mission and the ability to sell new ideas to the numerous, and dissimilar, people who can advance or impair the progress of the reliability of the missile.

5. He must be a diplomat in order that he may overcome the inertia and even the opposition of people, in some quarters, and secure their co-operation.

6. He should be a capable organizer.

Once the need of establishing a reliability group is recognized by the top management of a firm, it should be relatively easy to select qualified people from research and design staffs and assign them to this new task.

STABILITY AND CONTINUITY OF PURPOSE

In forming a reliability group one should realize that excellence and continuity of work are essential requirements for ultimate success, i.e., the attainment of a reliable missile. The analogy of the chain that is no stronger than its weakest link is valid also for the strength of the reliability group: The weakness or failure of a single member can easily delay the growth of the over-all reliability to such an extent that the missile type may become obsolete before it is reliable enough even to be considered for mass production.

For this same reason one should prevent frequent changes in the reliability group. Only specialists should be selected who are willing to stay with the reliability group, and their particular job, over a period of years, or preferably as long as the missile type is of importance to the fleet.*

Such reliability co-ordinators would then be able to accumulate a vast knowledge and experience about "their" missile that would make them highly qualified to indoctrinate the specialists of the fleet, and to control and maintain the reliability of the missile during training activities and in operational use.*

*See NAMTC Memorandum Report No. 29, "The German V-I Lecture," pages 3-8

conclusions

1. The particular difficulties in achieving and maintaining the over-all reliability of guided missiles necessitate that the growth of the over-all reliability be made the subject of careful planning.
2. It is suggested that a family of theoretical curves showing the typical growth of the over-all reliability be used as a guide for this planning and surveillance.
3. The success of a flight test program depends largely on the functional reliability of the flight test missiles. Consequently a reliability test program must be started at the very beginning of the missile development and must be accelerated by all conceivable means. Very high priority should be granted to such a reliability test program as a whole.
4. Reliability test programs must be conducted as long as a missile type is in development and production.
5. Reliability test programs must cover all conceivable "failure hazards" occurring from the stage of preliminary design through all stages of design, flight testing, production, transportation, storage, handling, and service use.
6. The cost of a reliability test program will be relatively small and be many times compensated by the savings of numerous expensive flight test missiles and by the huge savings of service missiles that otherwise would fail.
7. Time saving in the development of a guided missile weapon can be a decisive military factor. For this reason the acceleration of a reliability test program should be made a task of primary importance.
8. To achieve a maximum rate of growth of over-all reliability, appropriate priorities should be established within the reliability test program.
9. A "Priority Index," PI, is suggested that may help in rational determination of the test priorities. Such a priority index may also help to overcome severe bottlenecks in testing and may stimulate the co-operation of the designers in planning and conducting a reliability test program.
10. The Priority Index, PI, supplemented by several rules, can also be a guide for determining the appropriate sample size for each test case.
11. Because many of the critical stresses and conditions will not be known numerically in the early stages of a missile development, it is necessary that these stresses be conservatively estimated and specified for preliminary use in the development of the components.
12. The standardized components of a guided missile should be given first attention in reliability testing and for adaption to the missile.
13. Newly developed component types should not be used and expended in a flight test missile until they have attained a satisfactory reliability.
14. In the interest of a rapid growth of the over-all reliability, a prototype unit should be tested up to failure as extensively as feasible.
15. The knowledge that can be extracted from testing prototype units can be

greatly increased if the various kinds of tests are conducted in the proper sequence.

16. A single prototype unit, having been tested to failure, can be re-used for the subsequent categories of tests after the part that has failed has been repaired or replaced.

17. Nonavailability of a component for testing in the reliability program should be considered as an indication of poor organization, especially when such a component is intended to be used in a flight test missile.

18. Reduction of the severity of a stress or environmental condition is particularly desirable because not only one but many components will become more reliable through such reduction.

19. The testing of complex components suffering from multiple interdependent conditions requires considerable numbers of test units. For this reason such tests can be performed only in the later stages of development. Such components are the great liabilities to the development of a guided missile. They should therefore be avoided as much as feasible.

20. Sporadic detection and elimination of causes of failure must be supplanted by a determined systematic and comprehensive scrutiny, if rapid growth of the over-all reliability is to be attained.

21. It is imperative that the designer co-operate closely in the planning and conducting of a reliability test program. The personal care and responsibility for "his" component should extend over all stages of designing, testing, production, handling, and operation.

22. To penetrate the many critical reliability problems, the reliability co-ordinator will need the help of a group of highly reliability-minded specialists in the various fields of techniques related to guided missiles.

23. The reliability group must feel responsible for the ultimate functional reliability of a missile in service. It is therefore desirable that the reliability group "go with the missile" through all its stages of development, production, transportation and operation.

24. The activities of the reliability group will be centered in the development organization. The group should, however, be made responsible only to "top" management.

★ ★ ★